Grass evapotranspiration-induced suction in slope

Leung, Anthony Kwan

Published in:
Proceedings of the Institution of Civil Engineers: Environmental Geotechnics

DOI:
10.1680/envgeo.14.00010

Publication date:
2016

Citation for published version (APA):
Leung, A. K. (2016). Grass evapotranspiration-induced suction in slope: case study. *Proceedings of the Institution of Civil Engineers: Environmental Geotechnics*, *3*(3), 155-165. https://doi.org/10.1680/envgeo.14.00010

Grass evapotranspiration-induced suction in slope: Case study

---

Author 1

- Dr Anthony, Kwan LEUNG, PhD, Lecturer
- Division of Civil Engineering, University of Dundee, UK

Full contact details of corresponding author.

Address: Fulton Building, Division of Civil Engineering, University of Dundee, Nethergate, UK. Post code: DD1 4HN

E-mail: { HYPERLINK "mailto:a.leung@dundee.ac.uk" }

Telephone: +44(0)1382 384390

Fax: +44(0)1382 384389

Date of text written: 4th May 2014

Number of words in abstract: 197

Number of words in main text: 5725 (including references)

Number of tables: 1

Number of figures: 5

Abstract

Grass evapotranspiration (ET) have been recognised to potentially affect shallow slope stability due to additional soil suction induced by root-water uptake. Some limited field studies showed higher suction induced in vegetated soil than that in bare soil, but some reported the opposite. In order to improve the understanding of the hydrological role of grass ET, this study newly-interprets suction responses of grassed slopes based on the current knowledge of soil-water-root interaction on root-water uptake in unsaturated soil. Three case histories, which included measurements of suction in both bare and grassed slopes, are selected for investigation. It is revealed that during drying, ET-induced suction in grassed slope was not necessarily higher than that by evaporation in bare slope. When grass ET took place in relatively wet soil that has insufficient soil aeration (i.e., suction lower than that corresponding to anaerobiosis point; 5 – 12 kPa for sandy soil), induced suction in grassed slope could be 20% lower. During rainfall, the presence of grass appears to help retaining higher suction in slope comprising of silty clay, as compared to bare slope. On the contrary, for sandy soil, no discernible difference of suction retained between grassed and bare slopes is observed.

Keywords chosen from ICE Publishing list

Geotechnical Engineering; Environment; Field testing & monitoring

List of notation

AEV	Air-entry value [kPa]
AT	Actual transpiration [mm]
Δ	Slope of the vapour pressure curve [kPa $^oC^{-1}$]
e_s	Saturated vapour pressure [kPa]
e_a	Actual vapour pressure [kPa]
ET	Evapotranspiration [mm]
G	Soil heat flux density [J m^{-2} d^{-1}]
γ	Psychometric constant [kPa $^oC^{-1}$]
K_c	Crop factor [-]
k_s	Saturated water permeability of soil [m s^{-1}]
LAI	Leaf Area Index [-]
PET	Potential evapotranspiration [mm]
PT	Potential transpiration [mm]
PWP	Pore-water pressure [kPa]
R_n	Net radiation intercepted by plant leaves [J m^{-2} d^{-1}]

RH	Relative humidity in air [%]
T	Air temperature [^{o}C]
u	Wind speed [m s^{-1}]
WRC	Water retention curve [-]
ψ_{an}	Suction corresponding to anaerobiosis point [kPa]
ψ_{fc}	Suction corresponding to field capacity [kPa]
ψ_{wp}	Suction corresponding to wilting point [kPa]

1. Introduction

Vegetation has been recognised to potentially affect shallow slope stability through mechanical and hydrological effects (Barker 1995). In past decades, mechanical properties of vegetated soils have been researched for decades (Wu et al. 1988; Stokes and Mattheck 1996). The beneficial effects of mechanical root reinforcement are sometimes considered in slope stability calculation (Greenwood et al. 2004). In contrast, hydrological effects of plant evapotranspiration (ET) on induced soil suction (or negative pore-water pressure) receive relatively less attention. Although there were studies from agricultural literature investigating soil responses during plant ET, they mainly focused on changes of soil moisture and hydrological water balance due to the concern on crop yields (Wetzel and Chang 1987; Zhang et al. 2004; among others). As far as slope stability is concerned, it is more relevant to interpret and relate plant ET with suction, which has been generally recognised as one of the important stress-state variables governing unsaturated soil behaviour (Coleman 1962). Extensive research has demonstrated that an increase in suction would not only increase shear strength (Gan et al. 1988) but also decrease water permeability (Ng and Leung 2012), and hence rainfall infiltration.

In engineering literature, a number of field studies have been conducted to measure suction induced in vegetated soil slopes (Leung et al., 2011; Smethurst et al. 2012; Leung and Ng 2013a, b; among others). A few of them (Lim et al. 1996; Simon and Collison 2002; Kim and Lee 2010) included also suction measurements in bare slope, as control, to quantify any additional suction induced through root-water uptake. Based on these limited comparative studies, the hydrological effects of plant ET on induced suction is identified not to be consistent. It is found that vegetated soil could induce higher suctions than bare soil, but in some occasions opposite findings are observed, even within one single set of field data. The underlying reason causing this inconsistent observation is not well-understood.

In order to improve the understanding and identify the hydrological role of vegetation on the suction response in slope, this study newly-interprets the three field studies (Lim et al. 1996; Simon and Collison 2002; Kim and Lee 2010). The suction measurements reported in each study are analysed not only based on engineering properties of unsaturated soil, but also on the current understanding of soil-water-root interaction on root-water uptake in unsaturated soil. Due to limited case histories available in the literature, only hydrological effects of grass are investigated, whereas the effects of other plant species are not considered in this study.

2. Review of governing parameters of ET and grass-induced suction

Evapotranspiration of grassed soil is the sum of soil evaporation and grass transpiration. These processes depend on soil type, grass type, climatic condition and their interaction. Under given climatic conditions, potential evapotranspiration (PET) refers to the maximum value of ET when there is unlimited supply of water to replenish the associated loss of soil moisture. According to the well-known Penman-Monteith equation (Allen *et al.* 1998), which was derived based on energy balance, PET [mm] is revealed to be a function of a series of atmospheric parameters, and can be determined by:

{ EMBED Equation.DSMT4 } (1)

where Δ is slope of the vapour pressure curve [kPa $^{o}C^{-1}$]; R_n is net radiation intercepted by plant leaves [J m^{-2} d^{-1}]; G is soil heat flux density [J m^{-2} d^{-1}] (usually negligible due to the relatively small magnitude when compared to R_n; Allen *et al.* 1998); γ is psychometric constant [kPa $^{o}C^{-1}$]; T is air temperature [^{o}C]; u is wind speed [m s^{-1}]; (e_s – e_a) is vapour pressure deficit [kPa] (i.e., difference between saturated vapour pressure e_s and actual one e_a). The vapour pressure deficit is equivalent to relative humidity (RH) in air, which is defined as the ratio e_a to e_s; and K_c is crop factor (typically taken to be 1.0 for grass species; Allen *et al.* 1998).

Depending on Leaf Area Index (LAI), part of the PET would partition to potential transpiration (PT) based on the Beer's law (Ritchie 1972). PT refers to the maximum value of transpiration when root-water uptake is unlimited for a given soil type. For clipped grass investigated in the three studies, the LAI typically ranges from 1.5 to 2.2 (Allen *et al.* 1998). This means that about 55% – 65% of PET would contribute to PT. In most cases, actual transpiration (AT) is, however, lower than PT when soil becomes unsaturated. In plant physiology research, the relationship between AT and suction is represented by the so-called transpiration reduction function (Feddes *et al.* 1976; van Genuchten 1987), which reflects the ability of root-water uptake when ET takes place in soil having different initial wetness. When ET happens in relatively wet soil that has suction less than that corresponding to anaerobiosis point, ψ_{an}, transpiring stops (AT = 0) due to a lack of soil aeration (i.e., oxygen stress; Dasberg and Bakker 1970). When ET takes place in drier soil that has suction higher than ψ_{an} but lower than that corresponding to field capacity (ψ_{fc}), grass is considered to be at the most favourable condition for water uptake (AT = PT). In dry soil that has suction higher than ψ_{fc}, capillary force in soil becomes significant to retain water and hence suppress root-water uptake, commonly referred to as water stress (Hillel 1998; AT < PT). Transpiration ceases when suction reaches the wilting point ψ_{wp} (AT = 0).

In the literature, the ψ_{an} and ψ_{fc} is empirically reported to range from 1 to 5 kPa and from 40 to 80 kPa (Feddes *et al.* 1976, Indraratna *et al.* 2006; Nyambayo and Potts 2010), respectively, while ψ_{wp} is generally taken to be 1500 kPa. Based on the physical meanings of ψ_{an} and ψ_{fc}, they are anticipated to be strongly dependent upon the particle size distribution and hydraulic properties of unsaturated soils. The ψ_{an} is a measure of soil aeration and it thus depends on the diffusion rate of oxygen in soil. Many past experimental studies (Wesseling and van Wijk 1957; Vomocil and Flocker 1961; Kirkham 1994; MacKay *et al.* 1997) have shown that the gas diffusion practically stops when the air-filled porosity (i.e., volumetric air content) of soil is less than 5% – 10% for a wide range of soil types. The inability of gas diffusion in relatively wet soil would mean to have suppressed root metabolism and water uptake (Vartapetian and Jackson 1997; Armstrong and Drew 2002). For ψ_{fc}, it has been experimentally (Hillel 1998; Zacharias and Bohne 2008) and analytically (Meyer and Gee 1999; Twarakavi *et al.* 2009) identified that for various types of soil (1578 soil samples from the databases reported by Schaap *et al.* 2001 and Minasny *et al.* 2004), this parameter is related to water permeability and desorption rate (i.e., amount of water content drop due to an increase in suction) of soil. The higher the permeability or the desorption rate, the lower the soil moisture content is held at equilibrium, and hence the higher the ψ_{fc} is.

In addition, the ability of root-water uptake would also be affected by the characteristics of grass leaves and roots. This includes LAI, which controls the amount of solar radiation intercepted by grass leaves for partitioning PET to PT. Another governing parameter is Root Length Density (RLD), which is defined as the length of roots per unit volume of soil. At a given soil depth inside a root zone, higher RLD means to have more roots existed in soil for water uptake. Moreover, one possible mechanism that has been generally overlooked in literature is that the presence of root in soil pore space is likely to have altered soil pore size and its distribution. This would consequently results in a change of WRC and water permeability due to the potential blockage of water flow channels in soil pore (Scanlan and Hinz 2010; Scholl et al. 2014).

3. Selected case histories

Three case histories from three countries (Singapore, South Korea, and United States of America, USA) that are all situated in tropical, sub-tropical climate regions are selected for investigation. The three test sites are namely (i) Nanyang Technological University, Singapore (Lim et al. 1996), (ii) an express highway, South Korea (Kim and Lee 2010), and (iii) Goodwin Creek Experimental Watershed, USA (Simon and Collison 2002). In each case history, suction measurements in both bare and grassed soil slopes are available for direct comparisons.

3.1 Nanyang Technological University, Singapore (Case SGP)

The grassed slope tested in this site was 17 m high and has a uniform slope with an inclination of 30^{o}. The soil type was mainly silty clay, which has *in situ* saturated water permeability, k_s, of 1.0 x 10^{-6} m/s. A measured water retention curve (WRC) of the soil is shown in Figure 1. It can be seen that the air-entry value (AEV) of this fine-grained silty clay is considerably high (~150 kPa). The grass species covered on the slope was pasture, which has an average root depth of 0.1 m. More index properties of the soil and the grass are summarised in Table 1.

In this field study, the grassed slope was divided into two sections, one of which the top 0.1 m of the soil containing roots was excavated to form a bare slope, while the other section remained as is (i.e., grassed slope). In each slope, a number of tensiometers were installed to measure negative pore-water pressure (PWP) or suction at 0.5, 1.0, and 1.5 m depths.

3.2 An express highway, South Korea (Case SK)

The study slope in this case was also 17 m high and has a gradient of 29°. The soil type was clayey sand with gravel. The measured k_s of the soil was 1.2 x 10^{-5} m/s, which is an order of magnitude higher than that of the relatively finer soil type in Case SGP. The *in situ* measured WRC depicted in Figure 1 shows that the AEV of the coarse-grained soil is less than 1 kPa. The slope in this field study was partially vegetated with pasture, which has an average root depth of 0.2 m. The area where pasture was present is designated as grassed slope, whereas that without pasture is bare slope. In both the bare and grassed slopes, three tensiometers were installed at relatively shallower depths of 0.15, 0.3, and 0.45 m for measuring suction.

3.3 Goodwin Creek Experimental Watershed, Northern Mississippi, USA (Case USA)

The vegetated streambank investigated in this study was 3 m high and was made up of layers of loess-derived alluvium (fine sand). The bank was steep, generally between 70° and 90°. As shown in Figure 1, the AEV of the soil is 4 kPa. The grass species covered the streambank was clump grass, which has an average root depth of 0.5 m. Five tensiometers were installed at 0.3, 1.0, 2.0, 2.7, and 4.3 m depths in both the bare and grassed slopes for measuring suction.

In the following discussion, any effects of grass ET on (i) suction induced during drying period and (ii) suction retained during wetting period are explored. The magnitude and distribution of suction recorded in each case history are interpreted based on the current understanding of soil-water-root interaction on root-water uptake in unsaturated soil, as summarised in Section 2.

4. Results and discussions

4.1 Field observed pore-water pressure induced during drying periods

Figure 2 shows the measured responses of PWP distributions during two typical drying periods for all three selected case histories. In each case, a hydrostatic line representing the respective location of groundwater table is depicted for reference. After drying for 3 days in period 1 in Case SGP (Figure 2(a)), suctions in both the bare and grassed slopes increased, and the magnitude at 0.5 m depth in the grassed slope was 15% higher. In contrast, the peak suction induced in the bare slope in period 2 was higher than that in the grassed slope by not more than 10% (Figure 2(b)). However, it should not be misled that the comparisons between periods 1 and 2 are made under different suctions before drying. In fact, the amount of suction increase in the grassed slope in both periods 1 and 2 were larger than that in the bare slope consistently.

At deeper depths of 1 and 1.5 m, the difference of suction induced in the bare and the grassed slope is found to be indiscernible during both periods. This seems to suggest that the depth of influence zone of suction due to grass ET was less than 1 m, below which the suction was not likely to be affected by root-water uptake within the root zone (i.e., the top 0.1 m).

Similar to Case SGP, the suction gained in the grassed slope in Case SK (70 kPa) were more than that in the bare slope (40 kPa) during summer in period 1 (Figure 2(c)). However, in period 2 (Figure 2(d)), much higher suction (30 kPa) was recorded in the bare slope, whereas any suction induced by ET in the grassed slope seems to be negligible. This may be attributed to the reduction of root-water capability when grass ET took place in relatively wet soil (i.e., low suction; < 3 kPa) in period 2. The lack of soil aeration in wet soil (i.e., low oxygen diffusion rate) may have developed oxygen stress to grass, which consequently suppressed root metabolism and hence root-water uptake. More detailed discussion on any effects of oxygen stress on ET-induced suction is given in the next section.

During summer in Case USA (period 1; Figure 2(e)), larger suction increase was also recorded in the grassed slope than in the bare slope. In contrast, the response of suction recorded during winter (period 2; Figure 2(f)) were different from those exhibited in period 1 and those observed in the previous two cases. In this occasion, it is found that the amount of suction increase at 0.3 m depth in the bare slope (30 kPa) was twice as much as that in the grassed slope (15 kPa). Also, the peak induced suction in the bare slope (67 kPa) was 10% higher. Since any grass ET in this case took place in relatively dry soil (i.e., suction as high as 25 kPa or degree of saturation < 60%; see Figure 1), any effects of oxygen stress on root-water uptake might not be pronounced. Simon and Collison (2002), who reported this case history, argued that the lower suction induced in the grassed slope in winter time was attributed to grass dormancy, during which any root-water uptake might have ceased.

4.2 Identified hydrological effects of grass on induced suction during drying

To identify any hydrological effects of grass ET during drying periods, suctions measured before and after drying in all three cases are related in Figure 3. Note that every pair of data points taken from bare and grassed slopes has the same drying duration for fair comparison. When grass ET takes place in relatively wet soil having suctions less than 15 kPa, suction induced in grassed slopes by ET is 20% – 100% lower than that induced in bare slopes by evaporation (see inset). This is likely attributed to the lack of soil aeration as the build-up of oxygen stress may have suppressed root metabolism and hence root-water uptake. As discussed in Section 2, soil aeration is experimentally found to be sufficient when air-filled porosity of soil is higher than 5%–10%. It can be estimated from the WRC (Figure 1) that the suction (i.e., ψ_{an}) corresponding to this range of air-filled porosity is 1 – 5 kPa and 5 – 12 kPa for the soil in Cases SK and USA, respectively. When root-water take happened in soil having suction higher than this range of ψ_{an}, ET-induced suction in grassed slopes, in turn, became higher than evaporation-induced suction in bare slopes by at least 15% (Figure 3). This is because suction higher than the ψ_{an}

corresponds to degree of saturation below 70% (Figure 1), and any oxygen stress developed is likely to have relieved as air permeability at such low degree of saturation may be high enough for sufficient soil aeration.

For Case SGP, it is similarly observed that suction induced in the grassed slope was higher than that in the bare slope, when ET happened in soil that has initial suction ranging between 15 – 40 kPa (Figure 3). This is, however, somewhat unexpected. According to the WRC shown in Figure 1, the soil type (i.e., silty clay) encountered in this case appears to have greater water retention capability than those in the other two cases. For air-filled porosity of 5% – 10%, the corresponding suction (i.e., ψ_{an}) of this particular soil type is higher than 200 kPa. In other words, oxygen stress is anticipated to have been developed to suppress root metabolism when root-water uptake took place in the relatively wet soil with suction ranged between 15 and 40 kPa. While ψ_{an} seems to be a crucial factor that governs the ability of root-water uptake, this parameter is not only a function of the hydraulic properties of soil, but also depends on the grass type and its adaptability to climatic conditions. Direct measurement of this characteristic suction in the field is therefore not straightforward. As far as the author is aware, studies to quantify such complex dependency of soil-water-plant-atmosphere interaction on ψ_{an} are rare, even in the literature of plant physiology and agricultural research. Further investigation on ψ_{an} is needed to clarify the hydrological role of grass on ET-induced suction in relatively wet soil.

4.3 Field observed suction retained during rainfall periods

Measured PWP profiles before and after rainfall in each case history are shown in Figures 4(a) – (f). Each PWP response is obtained during a rainfall event, which happened right after the drying period reported in Figure 2. As shown in Figures 4(a) and (b), suctions in both the bare and grassed slopes comprising silty clay soil in Case SGP decreased after rainfall. In both periods 1 and 2, the grassed slope retained higher suctions than the bare slope by 20% – 250%. The additional suction retained in the grassed slope is, however, less likely attributed to grass root-water uptake. During rainfall, RH in air is usually high, while solar radiation is low due to cloudy condition. This is especially the case in humid tropical, sub-tropic climate regions (typically RH > 80% and radiation < 10 MJ/m^2/d; Leung and Ng 2013b), including the three cases investigated in this study. Under such climatic conditions, any grass ET during rainfall is likely to be negligible (refer to Equation (1)). Instead, the amount of suction retained appears to be dependent upon the amount of suction gained from previous drying period. It can be seen that suctions retained in the grassed slope at 0.5 m depth (25 and 50 kPa in periods 1 and 2, respectively) were higher when the suctions gained before rainfall (58 and 80 kPa in periods 1 and 2, respectively) were higher.

For Case SK (see Figures 4(c) and (d)), almost all suctions were reduced to less than 10 kPa in both the bare and grassed slopes after small rainfall intensity of 6.7 mm/d in period 1 and large intensity of 78.7 mm/d in period 2. It can be seen that the suction profiles measured after rainfall in the bare and grassed slopes comprising of clayey sand were close to each other, unlike the case observed in finer silty clay slopes in Case SGP. This means that for the soil type investigated in Case SK, higher suction gained from previous drying period in either bare or grassed slope did not necessarily help retaining higher suctions after subjecting to both rainfall events in periods 1 and 2. Any benefit due to higher suction gained from previous drying period by evaporation (for bare slope) and ET (for grassed slope) was not significant.

On the contrary, for the fine sand slopes investigated in Case USA, it is similar to Case SGP that suctions retained after both the rainfall with an intensity of 14 mm/d in period 1 (Figure 4(e)) and the rainfall with smaller intensity (3 mm/d) in period 2 (Figure 4(f)) were higher when suction induced before each rainfall event was higher. It should be noted that for the rainfall event in period 2, the increase in suction observed in the grassed slope below 2 m depth is because the influence zone of suction due to the small rainfall intensity was shallower than 2 m.

4.4 Identified hydrological effects of grass on suction retained during rainfall

To identify any hydrological mechanisms of grass that affects PWP responses during rainfall, correlations between PWP before and after rainfall are established in Figure 5 for the top 0.5 m near grass root zone. As shown in the figure, suctions (negative PWP) retained in Case SGP (both the bare and grassed slopes comprising of silty clay) after rainfall were higher when suction gained from previous drying periods were higher. This is because when suction before rainfall was higher, water permeability of soil would be lower (Ng and Leung 2012). This hence reduces infiltration when rainfall happens subsequently.

For a given initial suction, it can be seen that the final suction retained in the grassed slope in Case SGP was higher than that in the bare slope after rainfall. Moreover, the amount of suction drop in the grassed slope (33% – 66%) is much smaller than that in the bare slope (50% – 90%). One possible mechanism resulting in higher suction retained in the grassed slope might be attributed to the reduction of water permeability due to blockage of water flow channels by grass roots. This is consistent to the dataset interpreted by Huat et al. (2006) and Leung et al. (2014), who showed that infiltration rate in grassed soil was lower than that in bare soil. Such observed suction responses due to the presence of roots might be explained by a conceptual model proposed by Scanlan and Hinz (2010). This model suggests that if soil pore space is idealized as a capillary tube partially filled with water, the presence of roots in soil pore for a given RLD would lead to a decrease in the diameter of the water meniscus, and the associated change in soil suction would hence affect both WRC and water permeability (Scholl et al. 2014).

For Case USA, both the bare and grassed slopes comprising of fine sand also retained higher suctions when suctions before rainfall were higher. However, unlike Case SGP, the grassed slope did not appear to retain higher suction and did not show smaller suction drop than the bare slope. Any beneficial effects due to the presence of roots in the grassed slope seem not to be significant. Simon and Collison (2002) speculated that there was potential stemflow concentrating rainwater to depths of the grassed slope. The observed negligible difference of suction retained between the bare and grassed slopes in this case might be the consequence of the counteraction between the beneficial (reduction of water permeability due to root inclusions) and the detrimental (stemflow) hydrological effects of grass.

Rather different suction responses were exhibited in Case SK, as compared to the previous two cases. Data points collected from both the bare and grassed slopes comprising of clayey sand in this case distribute almost horizontally within a suction band between 2.7 and 5.3 kPa. Within this suction band, no major difference is found between the bare and grassed slopes, meaning that suction retained in both slopes after rainfall were independent of suction gained before rainfall. This is, however, not found in both Cases SGP and USA. This might be attributed to the difference of water retention behaviour of soil between the three cases. According to the WRC shown in Figure 1, it can be seen that for the same given increase in water content (due to rainfall infiltration), the decrease in suction for the coarser soil in Case SK is generally greater than that for the finer soil in other cases. Nevertheless, it should be noted that this comparison is more appropriate to be made based on wetting, rather than drying, WRC. Unfortunately, wetting WRC is not reported in all three cases for such comparison.

5. Summary and conclusions

This study explores and improves the understanding of the hydrological effects of grass on suction responses in grassed slopes situated in tropical, sub-tropical climate regions. Three case histories, which are the very few field studies documenting measurements of pore-water pressure responses in both bare and grassed slopes, were selected for new interpretation. Effects of grass roots on (i) suction induced during evapotranspiration (ET) and (ii) suction retained during rainfall are investigated in relations to the current understanding of soil-water-root interaction on root-water uptake in unsaturated soil. Based on the new interpretation of the three limited case histories, some key hydrological roles of grass may be identified, as follows:

(a) For the given climatic condition, it is revealed that ET-induced suction in grassed slope was not always higher than that induced by evaporation in bare slope. When ET took place in relatively wet soil that has suctions lower than that of aerobiosis point (i.e., ψ_{an}; 1 – 5 kPa for clayey sand and 5 – 12 kPa for fine sand), grassed slope induced lower suctions than bare slope by almost 20%. These ranges of ψ_{an} are found to correspond to the air-filled porosity of 5% – 10%. This matches the values identified from various past experimental studies, which suggested that within this range of air-filled porosity, any gas diffusion in soil would practically stop. The insufficient soil aeration would hence suppress the root-water uptake. In contrast, when grass ET took place in drier soil that has suctions higher than ψ_{an}, the suction induced in grassed slope was higher than evaporation-induced suction in bare slope by at least 15%.

(b) However, it is identified in one of the case histories that even though ET took place in soil that has suctions less than ψ_{an}, suction induced in the grassed slope comprising of silty clay was higher than that in the bare slope. While there is scarce research on ψ_{an}, further investigation is needed to quantify the ψ_{an} in relation to some factors that may account for the unexpected observation in this case history, including soil hydraulic properties, grass type, root characteristics as well as the adaptability of grass to climatic conditions.

(c) The effect of grass on suction retained during rainfall is revealed to be more significant for slope comprising of finer soil type than that of coarse one. During rainfall with intensity less than 20 mm/d, it is found that the grassed slope comprising of silty clay retained higher suction than bare slope, when comparing under the same given initial suction before rainfall. On the contrary, for sandy soil, no discernible difference of suction retained between grassed and bare slope is observed, regardless of the intensity of rainfall.

(d) It is identified that higher suction induced before rainfall did not necessarily result in higher suction retained after rainfall. When comparing the responses of suction retained between clayey sand slope and fine sand slope (both with vegetation), the decrease in suction in the former, coarser soil type is found to be greater than that in the latter, finer one, for a given rainfall event with similar intensity.

It must be emphasised that due to a lack of comparative field studies available in the literature, the above conclusions are drawn based on three specific case histories. As the response of ET-induced suction depends on many factors including soil type, grass type, climatic condition and their complicated interaction that are difficult to be differentiated, these conclusions should be treated with caution and not extrapolate the observations to general case. More comprehensive sets of field data that cover the measurements of suction and water content in both bare and grassed slopes and site-specific climatic data are needed to further examine the discussion given in this paper.

Acknowledgements

The author would like to acknowledge the research fund provided by the Northern Partnership Research, a research pool with significant funding support from the Scottish Funding Council involving University of Aberdeen, University of Dundee and the Robert Gordon University. Thanks also go to Prof. H. Rahardjo from Nangyang Technology University (NTU), Singapore and Dr Y. K. Kim from Korea Advanced Institute of Science and Technology (KAIST), South Korea, for their kind sharing of some information of their case histories presented in this paper.

References

Allen RK, Pereira LS, Raes D and Smith M (1998) *Crop evapotranspitation: Guidelines for computing crop water requirements*. Food and Agricultural Organisation's Irrigation and Drainage Paper 56

Amstrong W and Drew MC (2002) Root growth and metabolism under oxygen deficiency. *In* Plant roots: The Hidden Half (3rd edition), New York and Basel pp. 729–761.

Barker DH (1995) *Vegetation and slopes: stabilization, protection, and ecology*. Institute of Civil Engineers, London: Thomas Telford.

Coleman JD (1962) Correspondence: Stress/strain relations for partly saturated soils. Geotechnique 12(4): 348–350.

Dasberg S and Bakker JW (1970) Characterizing soil aeration under changing soil moisture conditions for bean growth. Agronomy Journal 62: 689–692.

Feddes RA, Kowalik P, Kolinska-Malinka K and Zaradny H (1976) Simulation of field water uptake by plants using a soil water dependent root extraction function. Journal of Hydrology 31(1): 13-26.

Gan JKM, Fredlund DG and Rahardjo H (1988) Determination of the shear strength parameters of an unsaturated soil using the direct shear test. Canadian Geotechnical Journal 25(3): 500–510.

Greenwood JR, Norris JE and Wint J (2004) Assessing the contribution of vegetation to slope stability. Proceedings of the Institution of Civil Engineers (ICE) – Geotechnical Engineering 157(4): 199–207.

Hillel D (1998) *Environmental Soil Physics*. Academic Press, San Diego, CA 92101-4495, USA.

Huat BBK, Ali FHJ and Low TH (2006) Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability. Geotechnical and Geological Engineering 24(5): 1293–1306.

Indraratna B, Fatahi B and Khabbaz H (2006) Numerical analysis of matric suction effects of tree roots. Proceedings of the Institution of Civil Engineers (ICE) – Geotechnical Engineering 159(2): 77–90.

Kirkham MB. (1994) Streamlines for diffusive flow in vertical and surface tillage: A model study. Soil Science Society of America Journal 58: 85–93.

Kim YK and Lee SR (2010) Field infiltration characteristics of natural rainfall in compacted roadside slopes. Journal of Geotechnical and Geoenvironmental Engineering ASCE 136(1): 248–252.

Leung AK and Ng CWW (2013a) Seasonal movement and groundwater flow mechanism in an unsaturated saprolitic hillslope. Landslides 10(4): 455–467.

Leung AK and Ng CWW (2013b) Analyses of groundwater flow and plant evapotranspiration in a vegetated soil slope. Canadian Geotechnical Journal, 50(12): 1204–1218.

Leung AK, Garg A, Coo JL, Ng CWW and Hau BCH (2014) Field study of infiltration rates and suctions in different vegetated grounds. Under review in Journal of Geotechnical and Geoenvironmental Engineering ASCE

Leung AK, Sun HW, Millis S, Pappin JW, Ng CWW and Wong HN (2011) Field monitoring of an unsaturated saprolitic hillslope. Canadian Geotechnical Journal 48(3): 339–353.

Lim TT, Rahardjo H, Chang MF and Fredlund DG (1996) Effect of rainfall on matric suctions in a residual soil slope. Canadian Geotechnical Journal 33(4): 618–628.

MacKay PL, Yanful EK and Rowe RK (1997) Diffusion coefficients of oxygen through unsaturated soils Proceedings, 50th Canadian Geotechnical Conference, Ottawa, October 2: 649–656.

Meyer PD and Gee G (1999) Flux-based estimation of field capacity. Journal of Geotechnical and Geoenvironmental Engineering 125(7): 595–599.

Minasny B, Hopmans JW, Harter TH, Tuli AM, Eching SO and Denton DA (2004) Neutral network prediction of soil hydraulic functions for alluvial soils using multi-step outflow data. Soil Science Society of American Journal 68: 417 – 429.

Ng CWW and Leung AK (2012) Measurements of drying and wetting permeability functions using a new stress-controllable soil column. Journal of Geotechnical and Geoenvironmental Engineering ASCE 138(1): 58–68.

Nyambayo VP and Potts DM (2010) Numerical simulations of evapotranspiration using a root water uptake model. Computer and Geotechnics 37(1 – 2): 175–186.

Ritchie JT (1972) Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research, 8(5): 1204–1213.

Scanlan CA and Hinz C (2010) Insight into the processes and effects of rootinduced changes to soil hydraulic properties. *In* 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane, Australia, 1– 6 August 2010. pp. 41– 44.

Schaap MG, Leij FJ and van Genuchten MT (2001) Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology 251(3–4): 163–176.

Scholl P, Leitner D, Kammerer G, Loiskandl W, Kaul H-P and Bodner G (2014) Root induced changes of effective 1D hydraulic properties in a soil column. Plant and Soil. Open Access, DOI: 10.1007/s11104-014-2121-x

Simon A and Collison A (2002) Quantifying the mechanical and hydrologic effects of riparian vegetation on strembank stability. Earth Surface Processes and Landforms 27(5): 527–546.

Smethrust JA, Clarke D and Powrie W (2012) Factors controlling the seasonal variation in soil water content and pore water pressures within a lightly vegetated clay slope. Geotechnique 62(5): 429–446.

Stokes A and Mattheck C (1996) Variation of wood strength in tree roots. Journal of Experimental Botany 47(5): 693–699.

Twarakavi NKC, Sakai M and Simunek J (2009) An objective analysis of the dynamic nature of field capacity. Water Resources Research 45(10) doi: 10.1029 /2009WR007944.

Vartapetian BB and Jackson MB (1997) Plant adaptation to anaerobic stress. Annals of Botany 79(Supplement A): 3–20.

Vomocil JA and Flocker WJ (1961) Effect of soil compaction on storage and movement of soil air and water. Transaction of the American Society of Agricultural Engineers 4(2): 242–246.

Wetzel PJ and Chang JT (1987) Concerning the relationship between evapotranspiration and soil moisture. Journal of Applied Meteorology and Climatology 26(1): 18–27.

Wesseling J and van Wijk WR (1957) Soil physical conditions in relation to drain depth. In Drainage of Agricultural Lands, American Society of Agronomy: Madison Wisconsin, 461–504.

Wu TH, Beal PE and Lan C (1988) In-situ shear test of soil-root systems. Journal of Geotechnical Engineering ASCE 114(12): 1376–1394.

van Genuchten MT 1987. *A numerical model for water and solute movement in and below the root zone*. Res. Rep. 121. USDA-ARS, US Salinity Lab, Riverside, CA, USA.

Zacharias S and Bohne K (2008) Attempt of a flux-based evaluation of field capacity. Journal of Plant Nutrient and Soil Science 171(3), doi: 10.1002/jpln.200625168.

Zhang Y, Kendy E, Qiang Y, Liu C, Shen Y and Sun H (2004) Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. Agricultural Water Management 64(2): 107–122.

Figure captions

Figure 1. Water retention curves of soil investigated in the three selected case histories

Figure 2. Measured pore-water pressure profiles upon drying for Case SGP in (a) period 1, (b) period 2, for Case SK in (c) period 1, (d) period 2, and for Case USA in (e) period 1, (f) period 2

Figure 3. Correlations of measured suctions before and after drying

Figure 4. Measured pore-water pressure profiles upon rainfall for Case SGP in (a) period 1, (b) period 2, for Case SK in (c) period 1, (d) period 2, for Case USA in (e) period 1 and (f) period 2

Figure 5. Correlations of measured PWP before and after rainfall near the root zone of grass

Table 1. Detailed comparisons of slope geometry, soil type, grass type and instrumentation among the three selected case histories

<table>
<tr><th colspan="3">Case</th><th>SGP</th><th>SK</th><th>USA</th></tr>
<tr><td colspan="3">Country</td><td>Singapore</td><td>South Korea</td><td>USA</td></tr>
<tr><td colspan="3">Climate</td><td>Tropical rainforest</td><td colspan="2">Humid subtropical</td></tr>
<tr><td rowspan="4">Slope geometry</td><td colspan="2">Height (m)</td><td>17</td><td>17</td><td>3</td></tr>
<tr><td colspan="2">Length (m)</td><td>25</td><td>30</td><td>3 – 4</td></tr>
<tr><td colspan="2">Slope angle (^{o})</td><td>30</td><td>29</td><td>70 – 90</td></tr>
<tr><td colspan="2">Water table (m below ground surface)</td><td>5 – 20</td><td>N.A.</td><td>2.75</td></tr>
<tr><td rowspan="13">Soil</td><td colspan="2">Type</td><td>Silty clay</td><td>Clayey sand with gravel</td><td>Fine sand</td></tr>
<tr><td rowspan="4">Particle-size distribution</td><td>Gravel (%)</td><td rowspan="3">15 – 50</td><td>25</td><td rowspan="6">N.A.</td></tr>
<tr><td>Sand (%)</td><td>48</td></tr>
<tr><td>Silt (%)</td><td rowspan="2">27</td></tr>
<tr><td>Clay (%)</td><td>50 – 85</td></tr>
<tr><td colspan="2">Plastic limit (%)</td><td>15 – 30</td><td rowspan="2">N.A.</td></tr>
<tr><td colspan="2">Liquid limit (%)</td><td>30 – 60</td></tr>
<tr><td colspan="2">In situ saturated water permeability (m/s)</td><td>1×10^{-6}</td><td>1.2×10^{-5}</td><td>N.A.</td></tr>
<tr><td colspan="2">Effective cohesion (kPa)</td><td>30</td><td rowspan="3">N.A.</td><td>1.4 – 6.3</td></tr>
<tr><td colspan="2">Friction angle, ϕ' (^{o})</td><td>26</td><td>27 – 28.5</td></tr>
<tr><td colspan="2">Friction angle with respect to an increase in matric suction, ϕ^b (^{o})</td><td>26 (suction less than 400 kPa)</td><td>10.2 – 17</td></tr>
<tr><td colspan="2">Air-entry value (kPa)</td><td>150</td><td>0.8</td><td>4</td></tr>
<tr><td colspan="2">Deduced suction value corresponding to the anaeriobiosis point (kPa)</td><td>> 200</td><td>1 – 5</td><td>5 – 12</td></tr>
<tr><td rowspan="2">Grass</td><td colspan="2">Type</td><td>Pasture</td><td>Pasture</td><td>Clump grass</td></tr>
<tr><td colspan="2">Root depth (m)</td><td>0.1</td><td>0.2</td><td>0.3</td></tr>
<tr><td rowspan="2">Installation depth of tensiometers</td><td colspan="2">Within root zone (m)</td><td>--</td><td>0.15</td><td>0.3</td></tr>
<tr><td colspan="2">Below root zone (m)</td><td>0.5, 1.0, 1.5</td><td>0.3, 0.45</td><td>1.0, 2.0, 2.7, 4.3</td></tr>
</table>

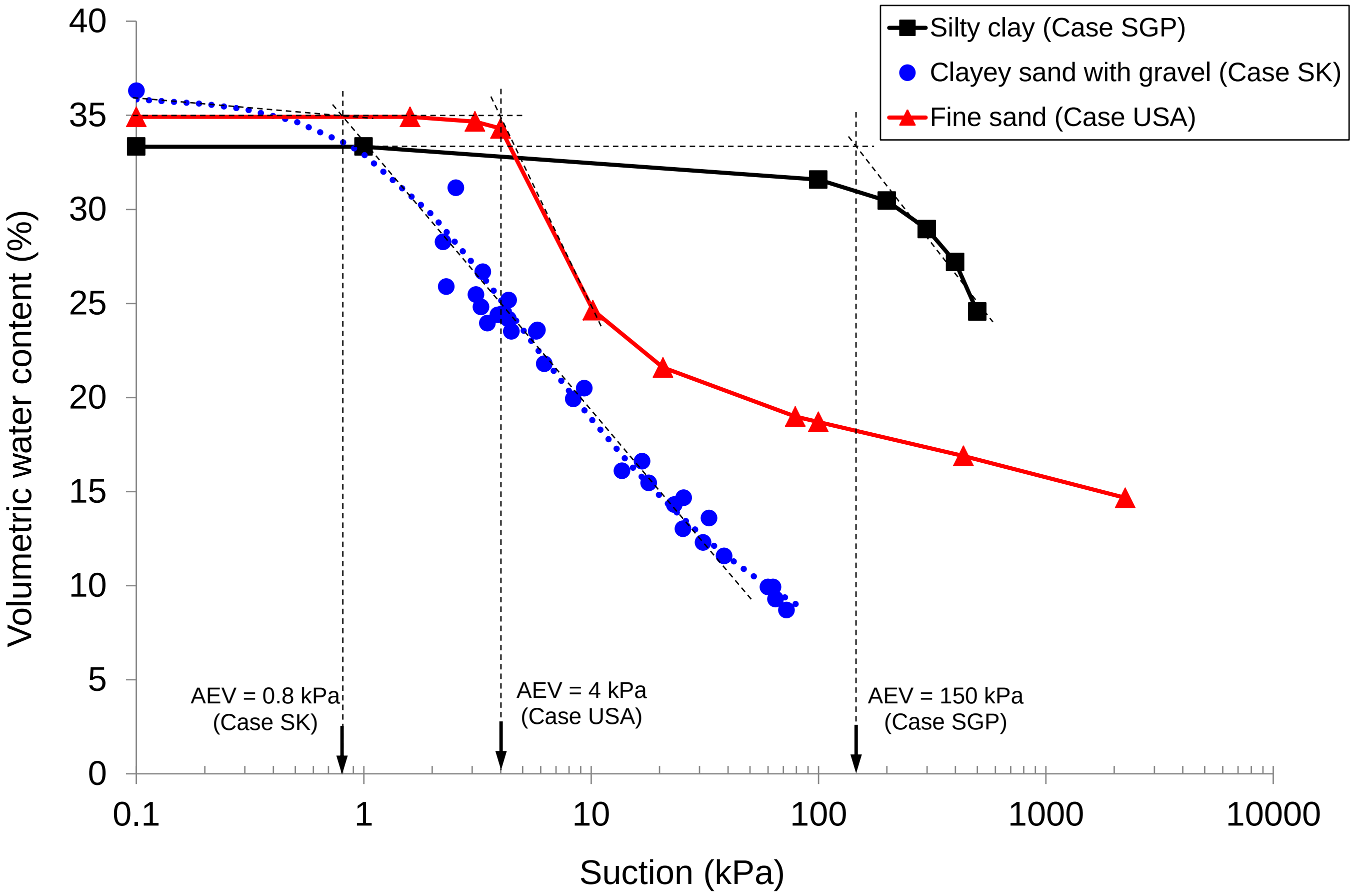
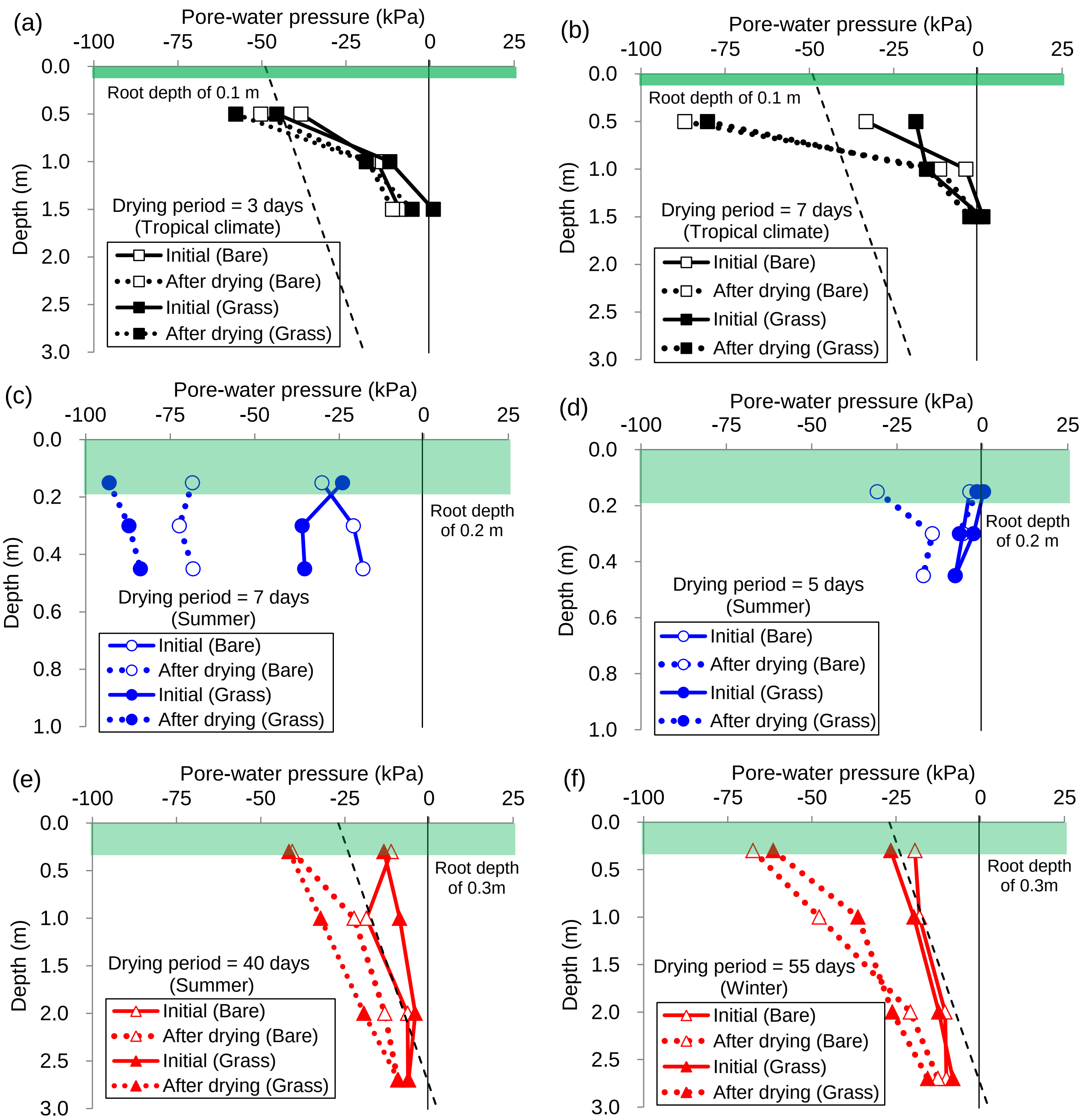


Fig. 1. Water retention curves of soil investigated in the three selected case histories



Note: Hydrostatic line is not given for Case SK since the depth of water table is not reported in Kim and Lee (2010)

Fig. 2. Measured pore-water pressure profiles upon drying for Case SGP in (a) period 1, (b) period 2, for Case SK in (c) period 1, (d) period 2, and for Case USA in (e) period 1, (f) period 2

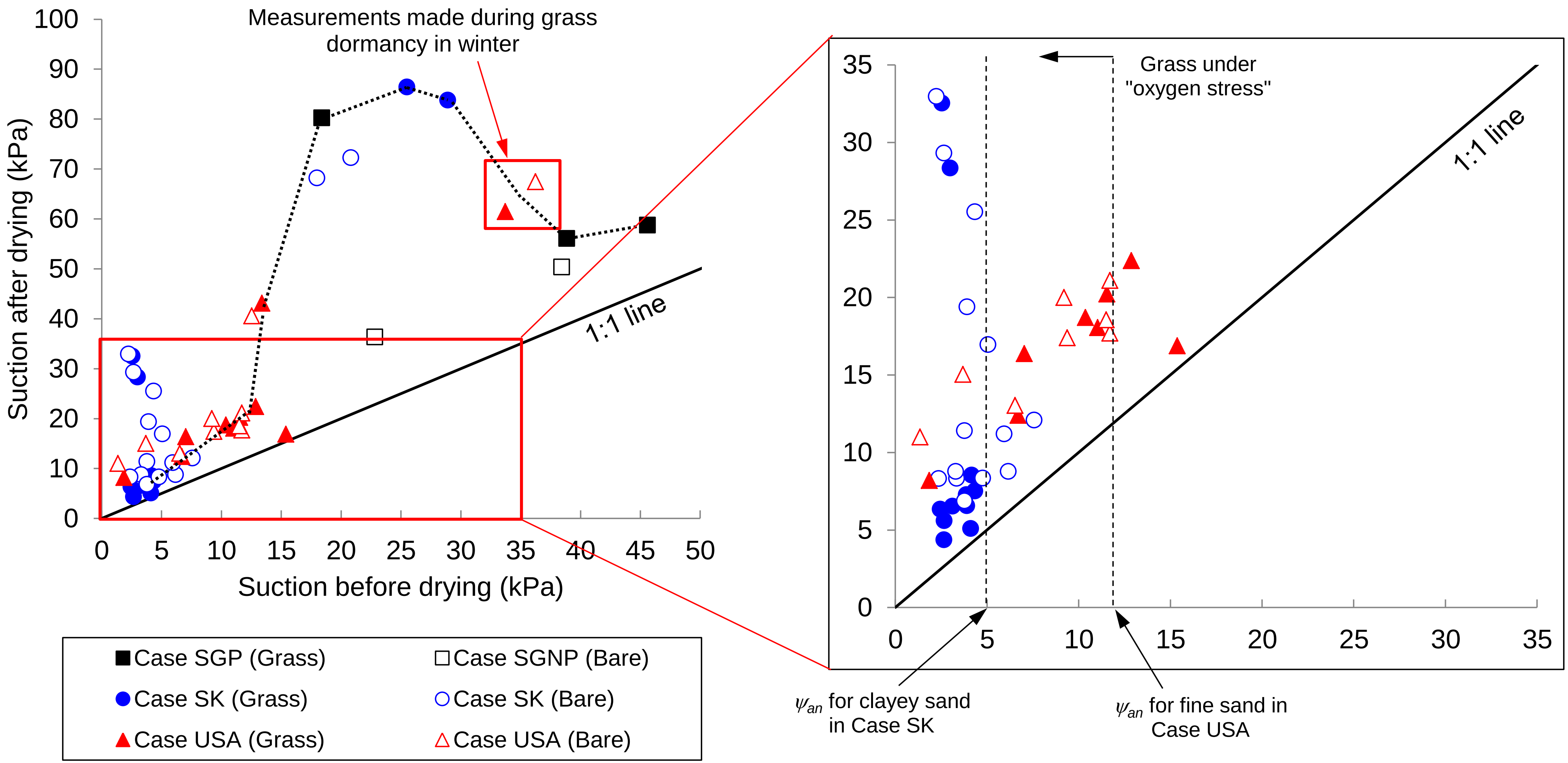
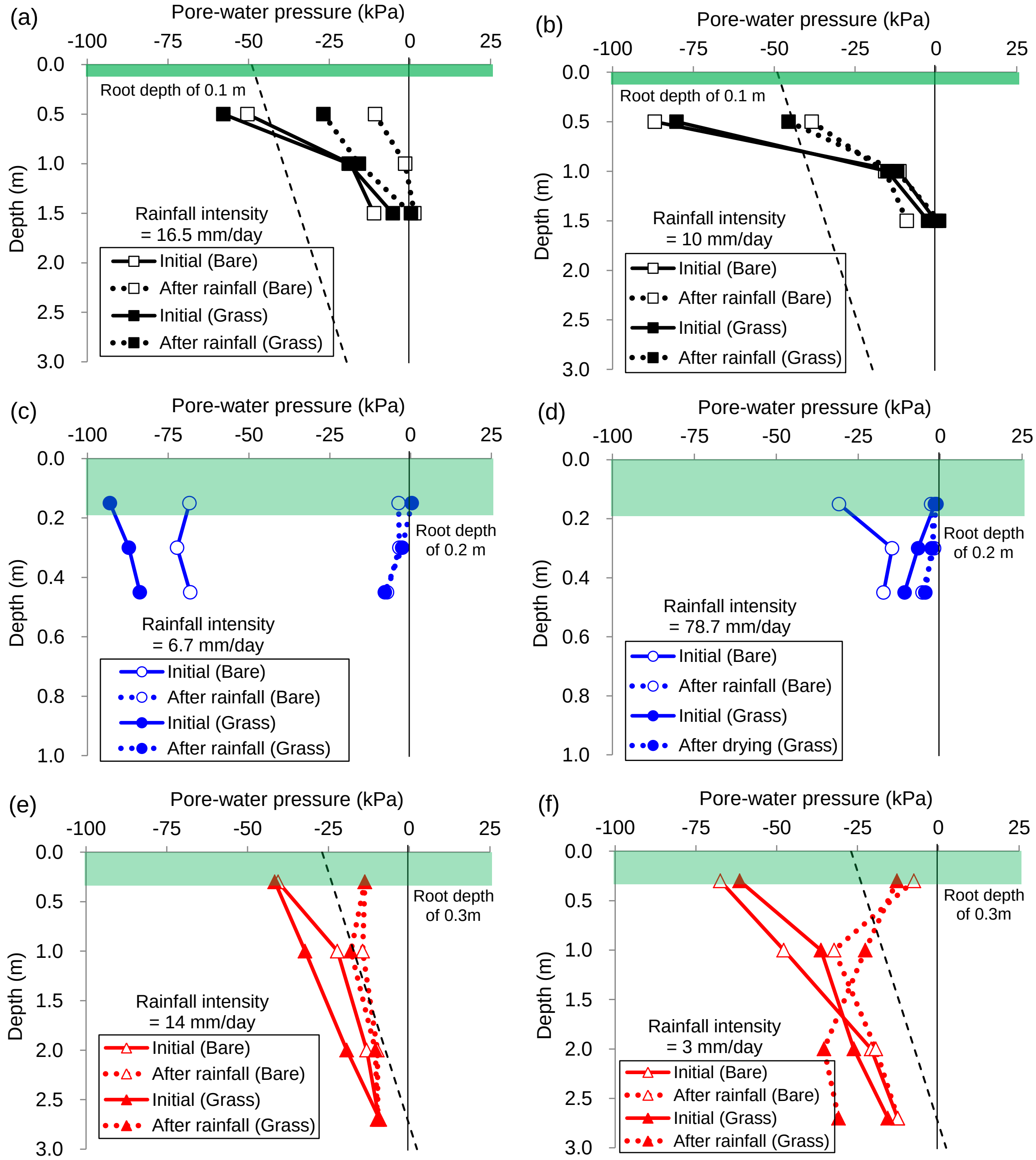


Fig. 3. Correlations of measured suctions before and after drying



Note: Hydrostatic line is not given for Case SK since the depth of water table is not reported in Kim and Lee, (2010)

Fig. 4. Measured pore-water pressure profiles upon rainfall for Case SGP in (a) period 1, (b) period 2, for Case SK in (c) period 1, (d) period 2, for Case USA in (e) period 1 and (f) period 2

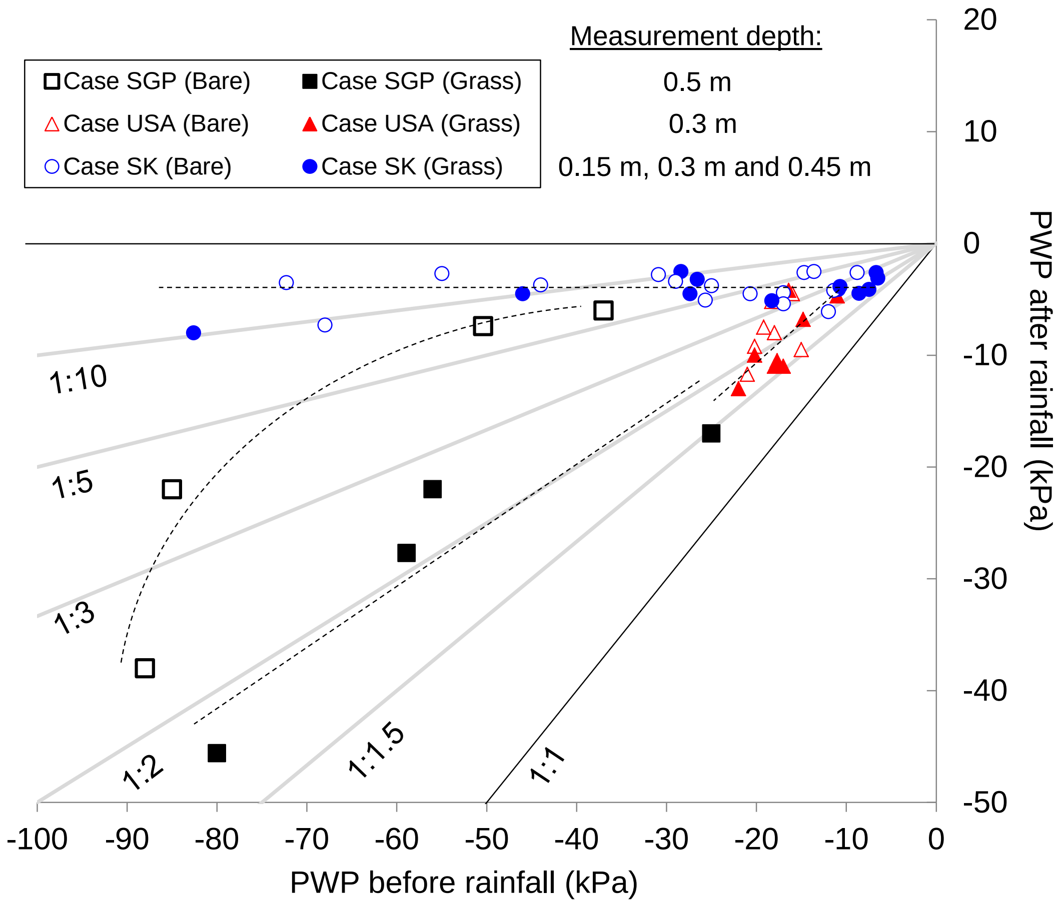


Fig. 5. Correlations of measured PWP before and after rainfall near the root zone of grass